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J_{Ic} MEASUREMENT POINT DETERMINATIONS FOR HY130, CMS-9 AND INCONEL 718

J.R. Matthews and G.D. West

March 1980

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FOR HY130, CMS-9, AND INCONEL 718

by

(10) James R. Matthews

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ABSTRACT

Determination of the elastic-plastic fracture toughness for three medium strength materials of varying ductility has been carried out. The materials in decreasing ductility are HY130 Steel, CMS-9 Steel, and Inconel 718. A survey of measurement-point techniques for J_{I_c} has been incorporated in the study to evaluate the effect of ductility on the determination of both an elastic-plastic fracture parameter and a fracture toughness measure for direct estimation of the elastic fracture toughness K_{I_c}.

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INTRODUCTION

Fracture toughness has been defined as the resistance of a material to fracture in the presence of a defect. Plane strain fracture toughness, K_{Ic}, (the elastic case) is the material-toughness property measured in terms of the stress-intensity factor K_I. In this case the stress-intensity factor is a measure of the stress-field intensity near the tip of an ideal crack in a linear elastic medium caused by displacing the crack faces apart. It is, in essence, the ability of the material to carry a load across the crack itself. When considerable plasticity is present, however, the elastic assumptions are invalid and consequently equations for calculating K_I are invalid and K_{I_c} becomes meaningless.

This creates a two pronged requirement for the development of an elastic-plastic fracture parameter and fracture toughness measure. The first is the need to define the point where fracture commences in an elastic-plastic component and the second is the need to relate the elastic-plastic result to the elastic result to permit the evaluation of the elastic plane strain fracture toughness by utilizing a small specimen that will yield prior to fracture.

This study is aimed at both these requirements and accordingly endeavours to define the elastic-plastic fracture toughness for three materials of different toughness, Inconel 718, HY130 and CMS-9 steel, and to predict the plane strain fracture toughness K_{I_c} for each of these materials using the small elastic-plastic specimens. In short, the purpose is to define the fracture behaviour of small specimens made from these materials and to acquire the fracture toughness for them without resorting to large specimen configurations.

BACKGROUND

The test procedure for determining plane strain fracture toughness for metallic materials (ASTM E399-74)[1] has gained acceptance as a measure of the material property K_{I_c}. However, its application is severely limited by the difficulty and expense of conducting tests on high toughness, lower strength materials. The specimen size must be large enough so that small amounts of non-linearity (yielding) surrounding the crack tip are embedded well within the linear elastic field and do not significantly disturb it. To perform a valid fracture toughness test under plane strain conditions, the size of the specimen must therefore increase with the square of the ratio

K_{Ic}/σ_y. This size requirement makes it almost impossible to measure high values of fracture toughness.

Based on Rice's J-integral,[2] the fracture criterion as proposed by Begley and Landes[3] has proven to be very useful in overcoming this size limitation. It permits measurement of fracture toughness from a specimen that has been fractured after general yielding because the fracture criterion is not based on the assumption of linear elastic behaviour. It is assumed that the onset of fracture is caused by a critical level of stress or strain and the associated critical level of potential energy being reached at or near the crack tip. This condition is measured with the J-integral, a two dimensional energy line integral defined by Rice as

$$J = \int_C \left(W\, dy - \sigma_{ij}\, n_j \frac{\partial ui}{\partial x}\, ds\right) \tag{1}$$

where W is the strain energy density, σ_{ij} is the stress tensor and u_{ij} is the displacement vector. On assuming that the crack coincides with the X-axis, C is an arbitrary path from its lower to upper surface, n_j is the outward normal vector to C, and S is the arc length along C.

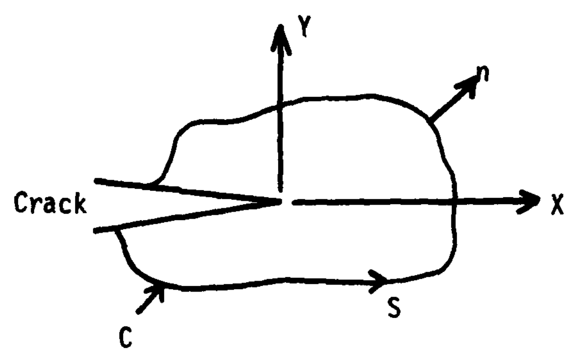

Figure 1. Idealization of crack.

The value of J is path independant for non-linear elastic materials.[4] More importantly, finite element calculations[5] have shown J to be approximately path independent for elastic-plastic materials as long as unloading does not occur. For this reason the J-integral would appear to be applicable only to the initiation stage of crack growth since propagation implies a partial unloading.

Rice[2,6] has also expressed J in terms of the elastic potential energy u as

$$J = -\frac{1}{B}\frac{\partial u}{\partial a} \tag{2}$$

where a is the crack length and B is the specimen thickness. This is identical to the strain energy release rate, G_I, of a linear elastic material and thus J is a direct extension of linear elastic concepts.

The evaluation of J by either equation 1 or 2 involves rather tedious calculations. However, for the ASTM three point bend specimen, Figure 2, Rice, Paris and Meckel[7] have developed the following expression which yields good results throughout the elastic-plastic region.

$$J = \frac{2A}{bB} \tag{3}$$

Here A is the area under a load vs load point displacement curve, B is the specimen thickness, and b the uncracked ligament. Underwood,[8] has developed an empirical equation for calculating the relative error due to including the energy effect of the uncracked specimen.

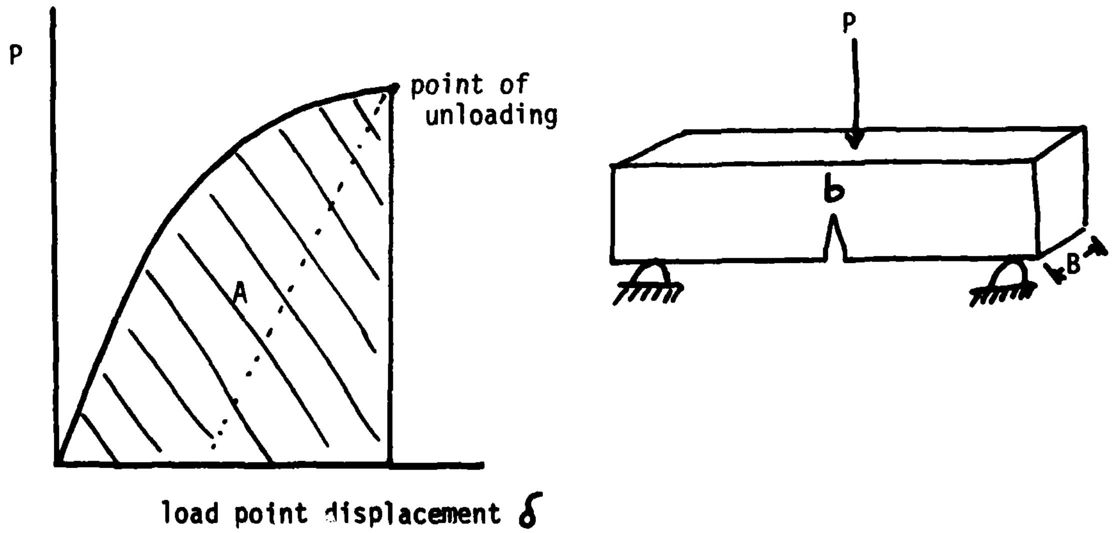

Figure 2. Determination of J from 3 point bend specimen.

The J-integral was originally used as an analytical tool for stress and strain determination at the crack tip. As such, the development of a J_{Ic} criterion was a logical extension of the original concept. This is illustrated schematically in Figure 3. Fracture starts from a sharp fatigue crack when the specimen or structure containing that crack is loaded beyond the prior cyclic loading level. At that point the crack tip becomes blunted. This blunting increases with the loading until at some critical stress the crack advances ahead of the original blunted flaw. This point is marked by a change in slope of a J vs crack extension curve since crack advance due to tearing ahead of the blunted crack develops at a much faster rate than the blunting process. J_{Ic} can then be determined by developing a curve of J vs crack advance (using multiple specimens) and marking the point of deviation from the blunting line.

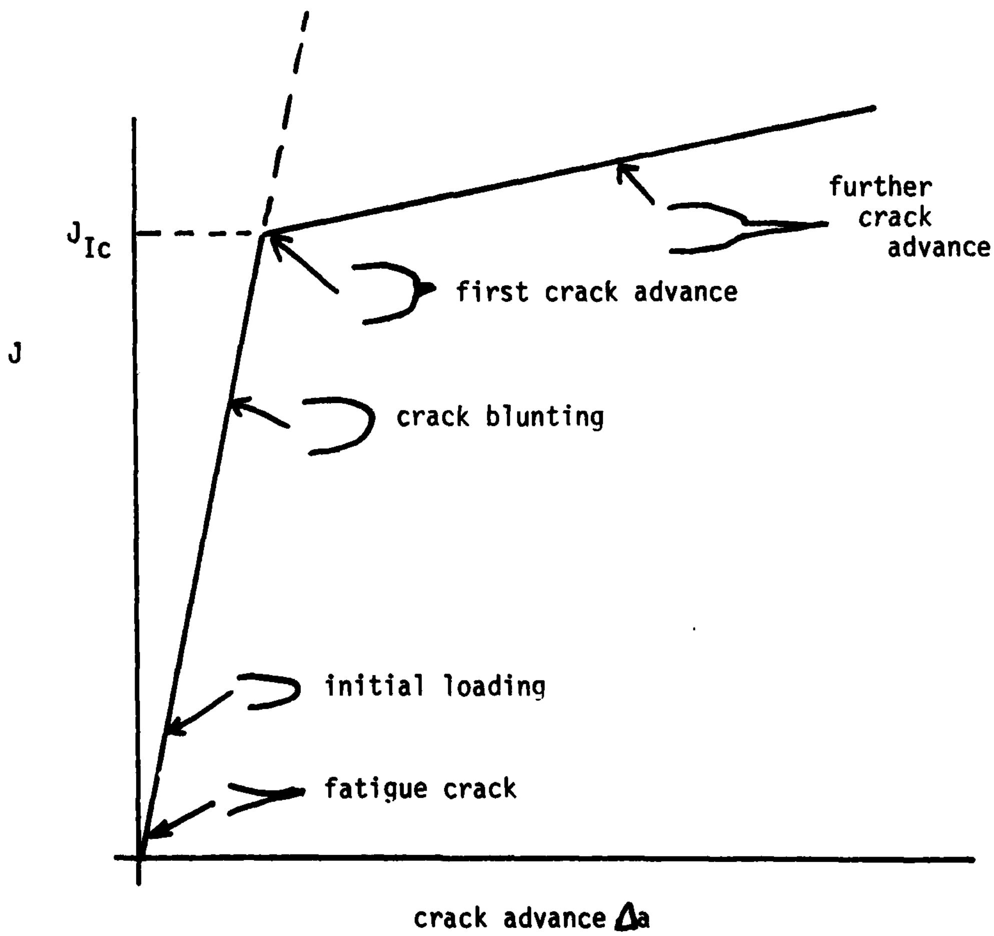

Figure 3. Representation of J vs Δa showing idealized point taken as J_{Ic} (after Landes and Begley[10])

J_{Ic} determined in this manner can be regarded as an elastic-plastic fracture criterion in its own right, or can be related to the more conventional linear elastic parameter K_{Ic} by the equation

$$J_{Ic} = G_{Ic} = \frac{(1 - \nu^2)K_{Ic}^{\ 2}}{E} \tag{4}$$

SIZE REQUIRFMENTS

The presence of size effects in fracture testing and component behaviour have been understood for some time. One effect, the crack length, has been related to the overall specimen size and the remaining ligament and has been accounted for by the use of the stress intensity factor K. The thickness B, has also been rationalized as it influences the transverse constraint. As thickness decreases, plane strain conditions give way to plane stress conditions.

It has been found that size effects are negligible if the minimum dimensions of the part exceed 50 times the plastic zone size, r_y. This concept is used by ASTM as the empirical requirement on size in the plane strain K_{Ic} test.[1]

$$a,\ b,\ B \geq 50\ r_y \doteq 2.5\ \left(\frac{K_{Ic}}{\sigma_y}\right)^2 \tag{5}$$

As mentioned earlier, size effects present severe difficulties in testing high toughness materials. For the HY130 and CMS-9 steels this would require specimens at least 2.25 and 1.10 inches thick respectively.

When using the J-integral as a failure criterion, specimens can be subject to large scale or general yielding; however, plane strain conditions must be present at the crack tip. It would appear that J is virtually thickness independent, providing the specimen is large enough for J to characterize the crack tip field. The minimum size requirement is expressed as

$$a,\ B,\ b \geq \alpha \frac{J_{Ic}}{\sigma_y} \tag{6}$$

where α is a non-dimensional constant of the order 25-50. The value of α has not been determined exactly as it may be material dependent. Using the upper α value of 50 gives minimum specimen sizes of 0.17 and 0.10 inches for HY130 and CMS-9 respectively, an order of magnitude smaller than the corresponding valid K_{Ic} specimens.

SINGLE SPECIMEN TEST

There have been a number of approaches to experimentally obtain J_{Ic} values using single specimen tests, as opposed to the multiple specimen test defined in the previous sections. Each single specimen test is designed to determine when the first crack advance has taken place. One is looking for a measurement technique which defines crack initiation. This might be done with acoustic emission, ultrasonics, optics or others, but these techniques are difficult to assess and have not been readily accepted.

A second single specimen test concept revolves around the multiple test technique but merely tries to reuse the single specimens for 3 or 4 individual crack advancing tests. Quite simply the fatigue crack is produced, the crack is advanced by controlled loading, a further fatigue crack is produced, the crack is once again advanced by controlled loading and so on. The difficulty here lies in the uncertainty associated with deformation of the specimen ahead of the crack tip region. The approach has more potential for low toughness materials as little specimen deformation would be associated with crack advance. This single specimen technique is examined in this report for each of the three materials, HY130, CMS-9 and Inconel 718.

The next technique for single specimen evaluation of the measurement point is that associated with the P-COD (Load-Crack Opening Displacement) curve. It has been postulated that a 5% change in the offset to this curve is equivalent to 2% crack growth.[1] This will be looked at in detail for each of the three materials evaluated in this work.

Another single specimen technique, not tried in this work but indicating promise, is that of Clark.[11] In this case the load is decreased by 10%, increased then decreased by 10% successively until a significant change in the unloading angle is noted. This is assumed to be associated with crack advance and taken as the measurement point for J_{Ic}. The difficulty here lies in the available sensitivity of load crack opening devices and computer enhancement techniques to assess the measurement point.

MATERIAL AND PROCEDURE

The materials evaluated were CMS-9 steel, Inconel 718 and Air Melted Vacuum Degassed (AMVD) HY130 steel. The composition and mechanical properties of these metals are given in Tables 1 and 2. All of the specimens were of the notched bend bar type, Figure 4a and 4b, loaded in three-point bending. Specimen dimensions are listed in Table 3.

In all cases the specimens were of the L-T crack orientation. (The L-T crack orientation corresponds to that of a full thickness crack stressed parallel to the rolling direction, L, and propagating across the plate width, T, that is, perpendicular to L.).

TABLE 1

Material	%C	%S	%Mn	%Si	%Ni	%Cr	%Mo	%V	%Nb &Ta	%Ti	%Al	%Cu	%Fe	
HY130	0.10	0.012	0.78	0.30	5.3	0.59	0.49	0.06	-	-	-	-	-	bal
CMS-9	0.17	.013	1.30	0.30	-	-	0.29	-	-	-	-	-	-	bal
INCONEL 718	0.08	0.015	0.35	0.35	45	18	3	-	5.15	1.05	0.70	0.30	-	bal

TABLE 2

Material	Yield Strength	Tensile Strength
HY130	∿130 ksi	145 ksi
CMS-9	162	178
INCONEL 718	154	∿200

TABLE 3

Material	Width B	Thickness W	Length L
HY130	1.000 in	1.000 in	9 in
CMS 9	.500	1.000	9
INCONEL 718	.525	1.500	12

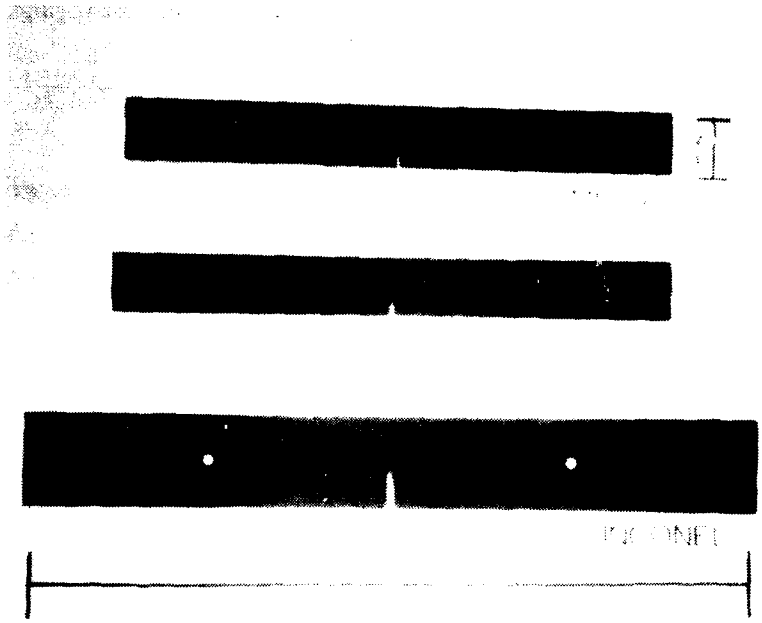

Figure 4a. Side view of test specimens

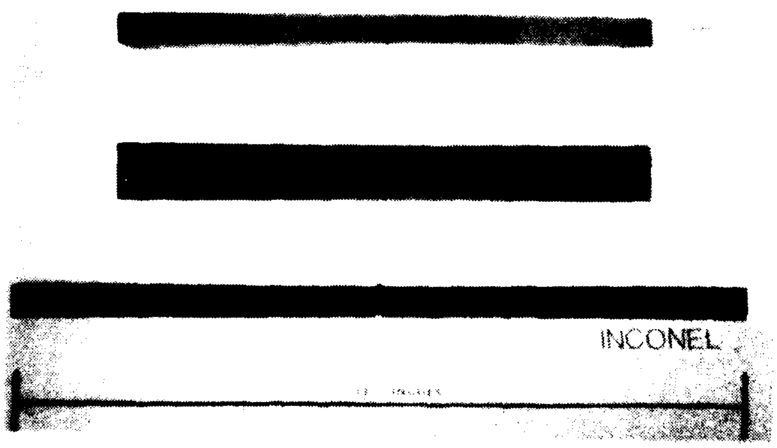

Figure 4b. Bottom view of test specimens

The as-received HY130 samples had been austenitized at 830°C for 93 minutes, water quenched, then tempered at 645°C for a further 93 minutes. The CMS-9 stock was austenitized at 940°C, water spray quenched, then tempered at 400°C. No times were reported for the CMS-9 heat treatment.

Inconel nickel-chromium alloy 718 is an age hardenable austenitic material. The mechanical properties of this niobium-aluminum-titanium hardened alloy are determined by the heat treatment received. Unfortunately, this information was not available for the Inconel stock used in this experiment.

Photomicrographs of the materials in the as-tested condition are shown in Figures 5a through 5d. The HY130 and CMS-9 steels show typical quenched and tempered structures. While these structures should produce a high strength, tough material, the heavily precipitated grain boundaries of the Inconel would provide preferential crack paths for intergranular fracture and reduce its toughness.

All of the specimens were mounted in the ASTM testing jig and pre-cracked in tension-tension fatigue using a closed loop servo-hydraulic testing unit, Figures 6a and 6b. The crack lengths were extended beyond the notch root to obtain nominal crack length to specimen width ratios (a/w) of 0.6. Crack growth during fatigue was monitored at the specimen surface by means of a microscope and graduated eyepiece. Care was taken not to influence the fracture characteristics of the material by ensuring a sufficiently low fatigue load level and stress intensity, in all cases corresponding to less than 50% of the critical values.

The specimens were then monotonically loaded under stroke control, Figures 6a and 6b. The load versus ram displacement and load versus crack opening displacement (COD) were recorded on separate X-Y plotters. The loading rate was 0.05 in/min and all tests were done at room temperature (21-22°C).

Heat tinting for 10 minutes at 350°C was used to mark any crack advance in the steel specimens, Figure 7. The Inconel could not be heat tinted at a reasonably low temperature so the crack advance was marked by fatigue post-cracking, Figure 7. If the remaining ligament was large enough (a/w <0.85), fatigue loading was used to square up the crack front and extend the crack out of the deformed region. In this way more than one test could be performed on a single specimen.

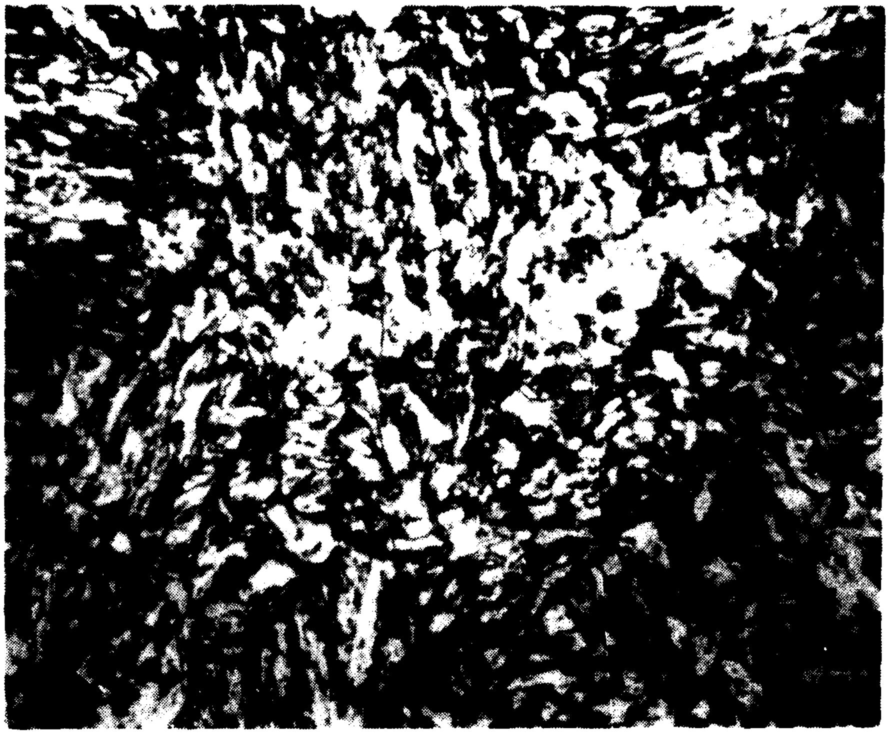

Figure 5a. HY130 Structure (1000x)

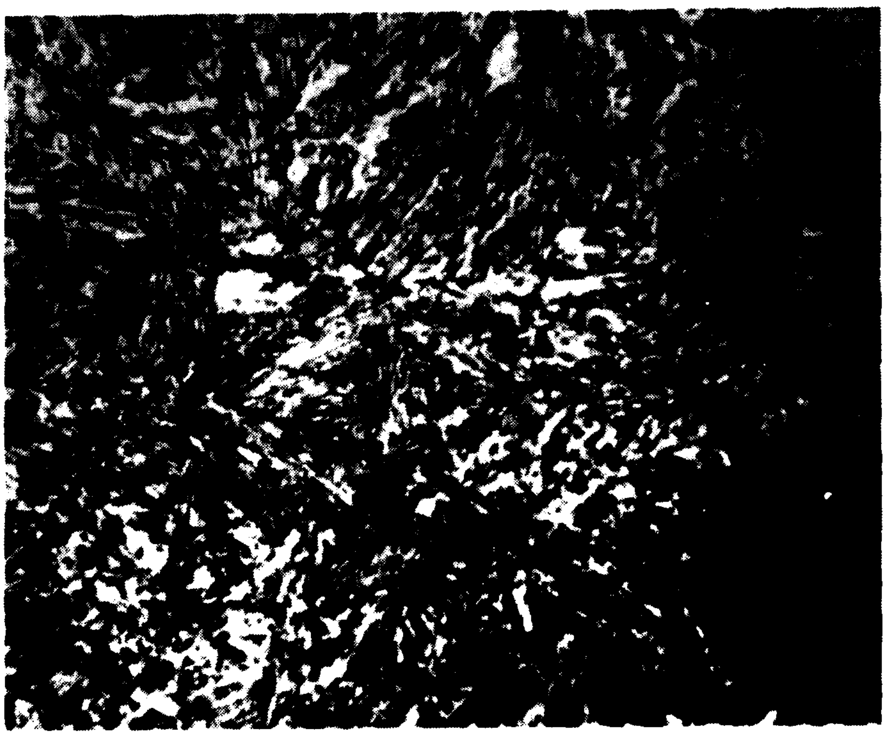

Figure 5b. CMS-9 Structure (1000x)

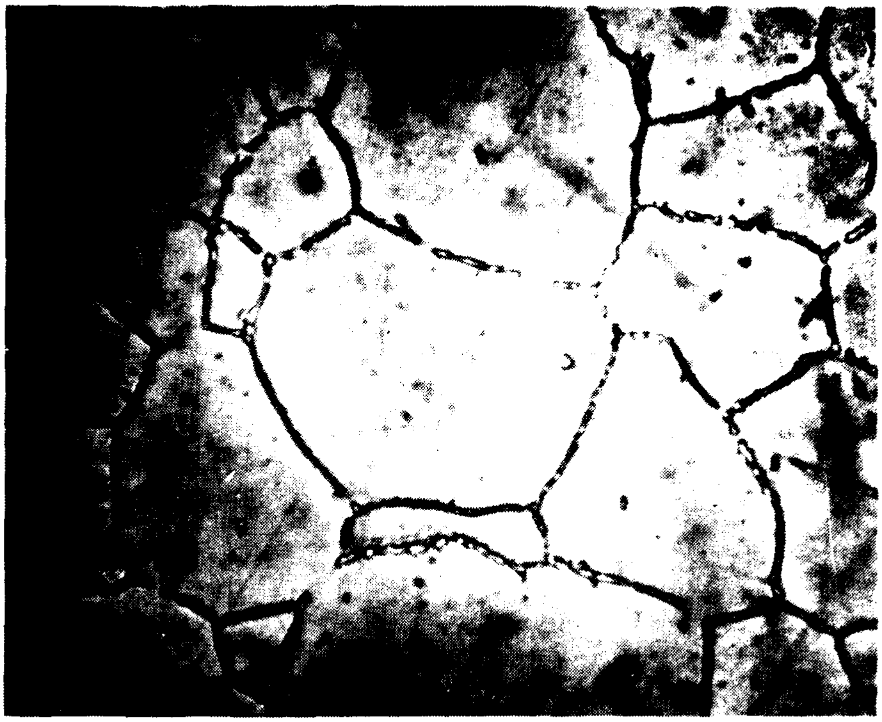

Figure 5c. Inconel Structure (1700x)

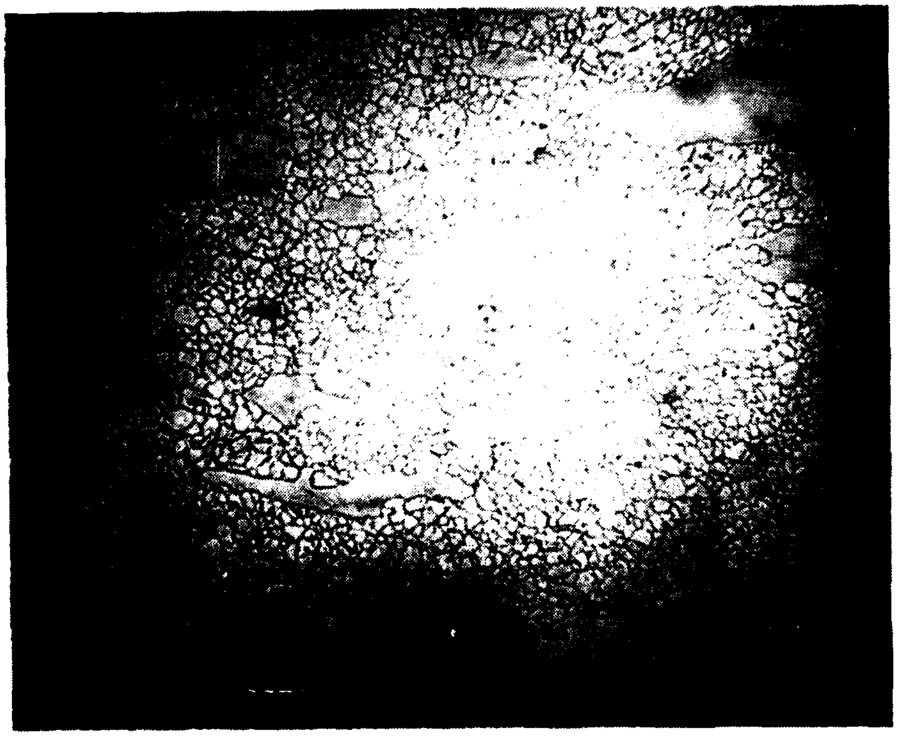

Figure 5d. Inconel Structure (100x)

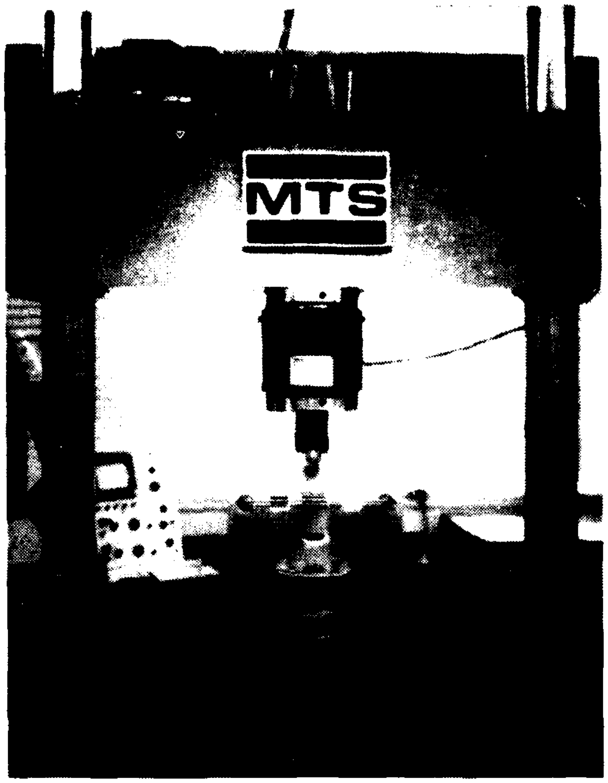

Figure 6a. Specimen jig and Inconel specimen awaiting test.

Figure 6b. MTS Control Console

After the final test the specimens were broken open. The crack advance that occurred during monotonic loading was easily distinguished from the areas of fatigue on the fracture surface, Figure 7. The minimum remaining ligament after precracking b_o and the maximum value of Δa were measured from the fracture surface. The area A under the corresponding load - deflection curve was measured using a planimeter and converted to energy units.

Figure 8 shows schematically the various measurement points considered and how the area under the P-δ curve was measured from that curve. A' was designated as the point on the load-crack opening displacement curve where an offset of 5% on the curve was noted; Amax was taken at the point where the load was maximum; A was taken at the point of obvious crack extension and A* was taken at any point where a test was terminated by intentional unloading. Equation 3 was used to calculate J which was then plotted against crack extension Δa in the form of a resistance curve.

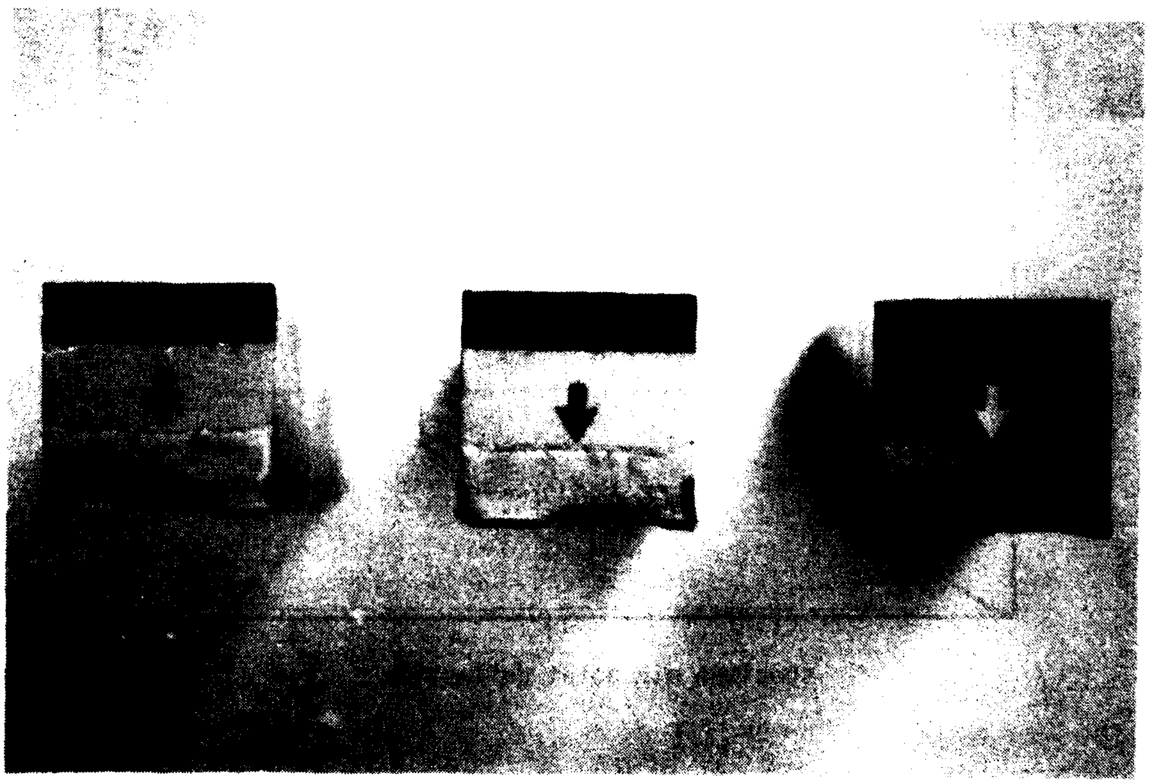

Figure 7. Test specimens showing tinting (specimen on right) and use of fatigue loading to define narrow strip of crack extension; (two specimens on left).

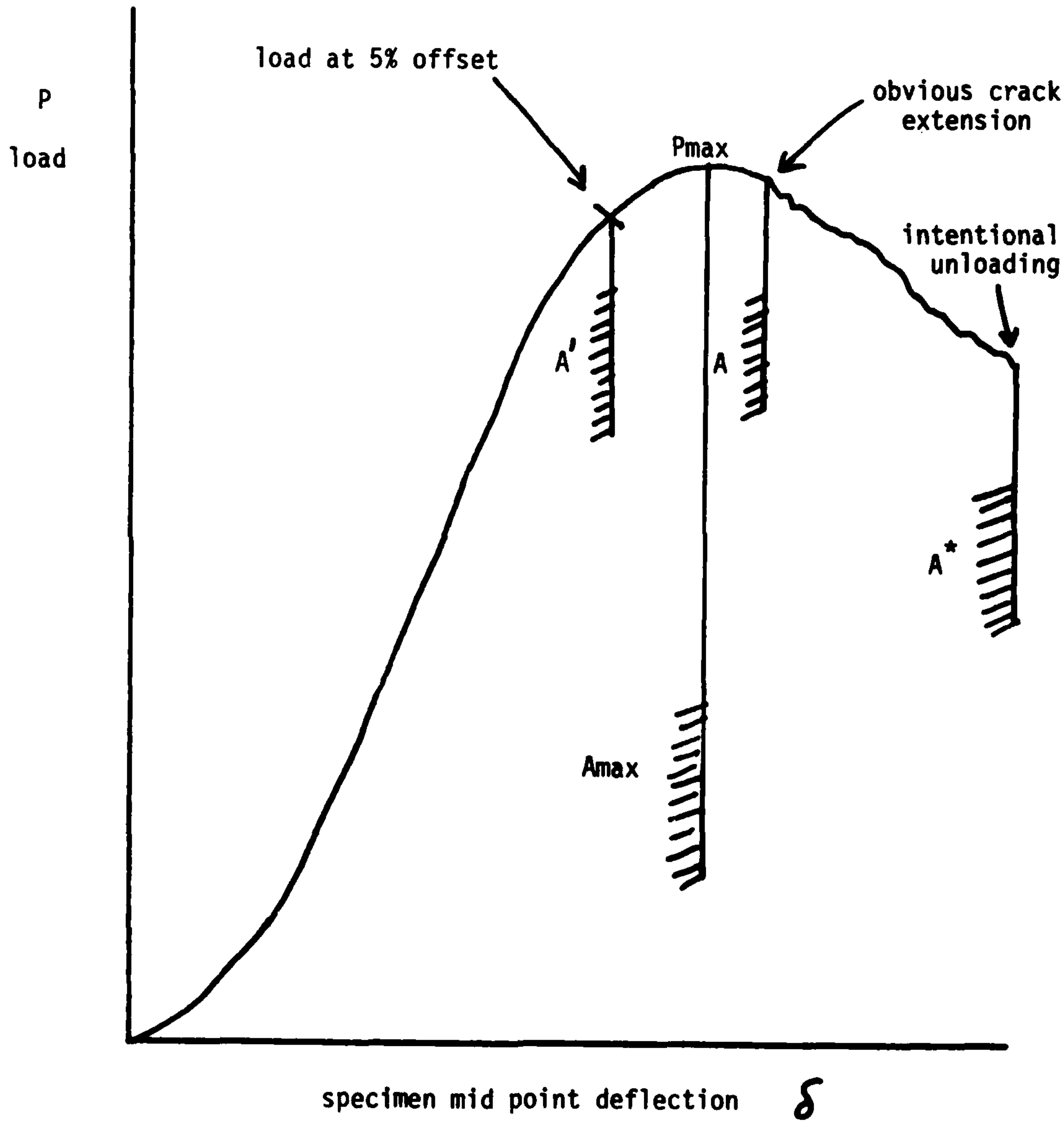

Figure 8. Schematic for various load point designations.

These curves are detailed in the results.

In order to use Equation 3, the uncracked ligament must be subjected primarily to bending stresses[9] and yielding of the specimen must be confined to this region. The area referred to in Equation 3 should theoretically be only that part of the load deflection curve due to the introduction of a crack. Therefore, the portion of the area contributed by an uncracked specimen should be subtracted out. However, empirical evaluations[8] have shown that more accurate values of J over greater ranges of crack length can be determined if the total area, due both to the cracked and uncracked contributions, is used. This approximation is accurate to within a few percent for values of a/w greater than 0.5 where the energy absorption component of the uncracked body is small. The crack lengths used in this investigation, a/w >0.6, satisfy both the ligament yielding and area conditions.

RESULTS

1. HY130

The load deflection curves for 8 specimens are shown in Figure 9. In the first 5 tests the loads were removed at the indicated stops because the load vs crack opening offset had exceeded 5% and it had been presumed that crack advance had taken place giving points both on the crack blunting line and crack advance line. On breaking open each of these specimens no crack extension was discovered, even after examination in the transmission electron microscope. In the remaining three tests the load was taken through a maximum, and beyond the point of obvious crack extension to acquire various points on the crack advance line, Figure 10. J* values are plotted against Δa for points where the tests were terminated by intentional unloading. For those tests where no crack extension was discovered the points were plotted on the crack blunting line. J max values [determined from the maximum load] as well as J values (obvious crack extension) were plotted beside the crack blunting line. J_{Ic} would lie below the J values for obvious crack extension, in the vicinity of the J max values and possibly at the intersection of the R-curve with the crack blunting line. This is discussed further later with the measurement point for the other materials. A complete tabulation of the HY130 data is contained in Table 4.

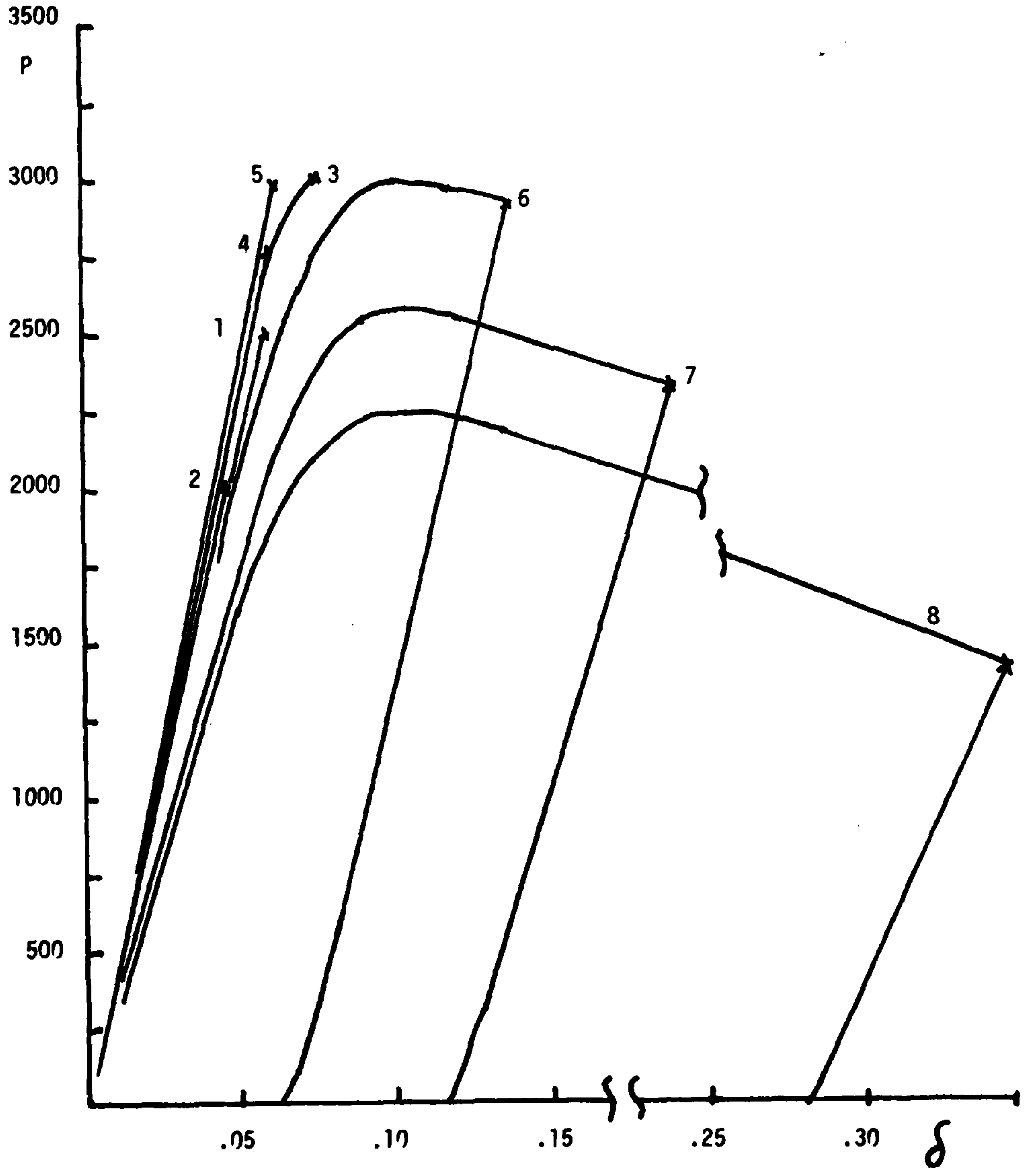

Figure 9. Load deflection curves for HY130 Specimens.

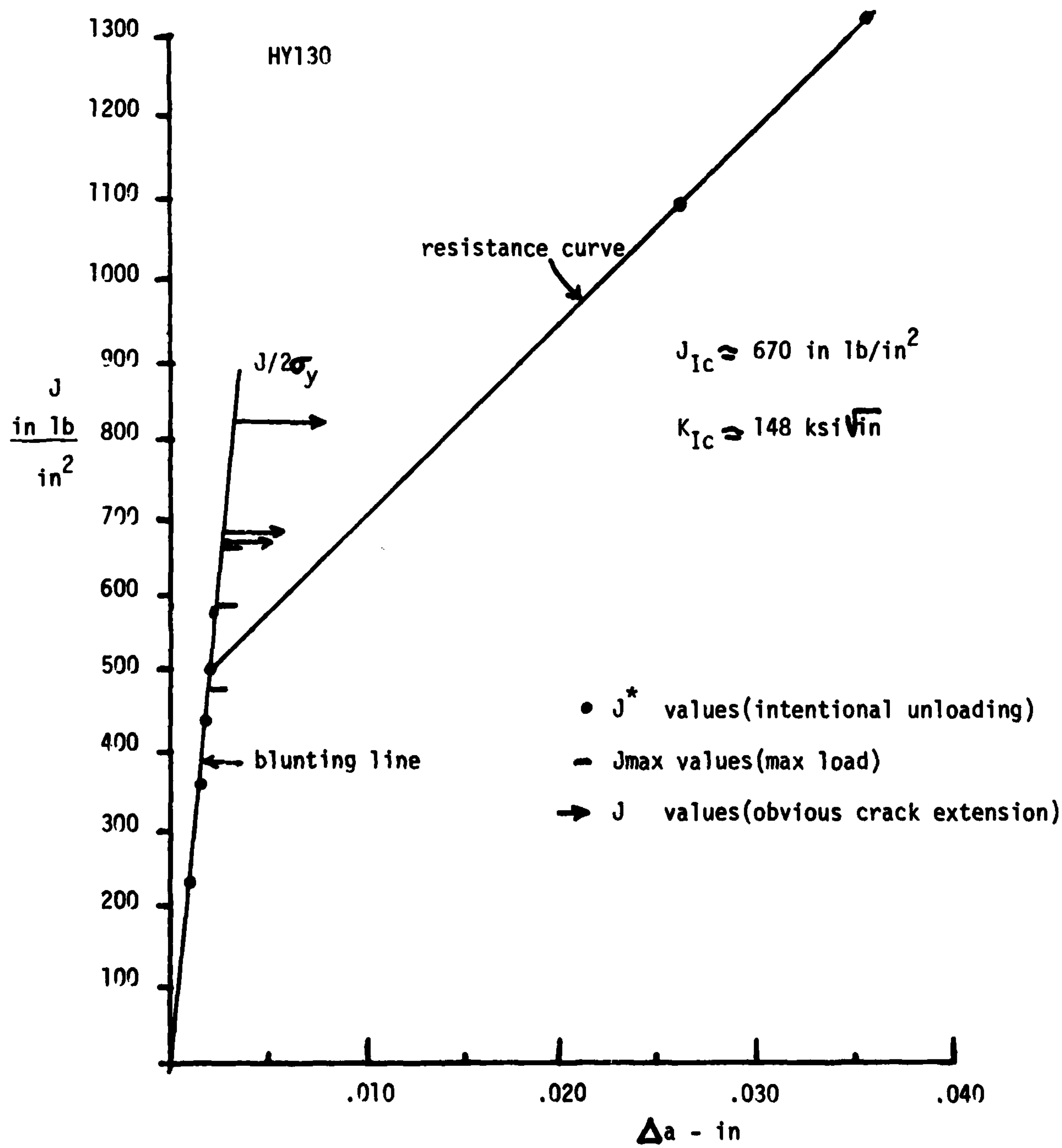

Figure 10. Graphical determination of J_{Ic} for HY130.

TABLE 4

Test Results for HY130 (σ_y = 130 ksi, σ_u = 145 ksi) (A: in.lb, J: in.lb/in^2)

Specimen	1	2	3	4	5	6	7	8
B (in)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.95
W (in)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	.936
Δ_a(in)	-	-	-	-	-	.025	.034	.081
b_o (in)	.412	.407	.420	.425	.425	.595	.618	.650
b_f(in)	-	-	-	-	-	.570	.584	.569
A max (max load)	-	-	-	-	-	189	171	148
A^1 (5% offset)	45.3	-	48.6	42.2	52.7	-	-	-
A (obvious crack extension)	-	-	-	-	-	235	203	209
A* (intentional unloading)	74	47	123	95	107	294	365	578
J max$_o$	-	-	-	-	-	671	584	479
J^1_o	220^+	-	231^+	198^+	248^+	-	-	-
J_o	-	-	-	-	-	831	693	677
J^*_o	361	232	586	446	503	-	-	-
J^*_f	-	-	-	-	-	1085	1316	2141

+ meaningless criteria for this material.

2. Inconel 718.

Load deflection curves for four Inconel specimens are shown in Figure 11. For these specimens the maximum load came just prior to the 5% offset point which was just after the point of obvious crack extension. The R-curve was plotted for the Inconel specimens and is shown in Figure 12. J values (corresponding to the 5% offset point) J_o and J max values (corresponding to obvious crack extension and point of maximum load) and the intercept of the R-curve with the crack blunting line all occur at the same point. The stars on the graph are points acquired in second tests on these specimens. Table 5 shows the data for the Inconel 718 specimens.

3. CMS-9 Steel.

Load deflection curves for 4 specimens of CMS-9 are shown in Figure 13b. The R-curve, Figure 14, shows that the crack blunting line and R-curve intercept coincide with the 5% offset point, and just under the obvious crack extension point. Complete data for the CMS-9 specimens are shown in Table 6.

DISCUSSIONS

Choosing a measurement point for J_{Ic} is the most important aspect of elastic-plastic fracture toughness determination. The following measurement points have been suggested:

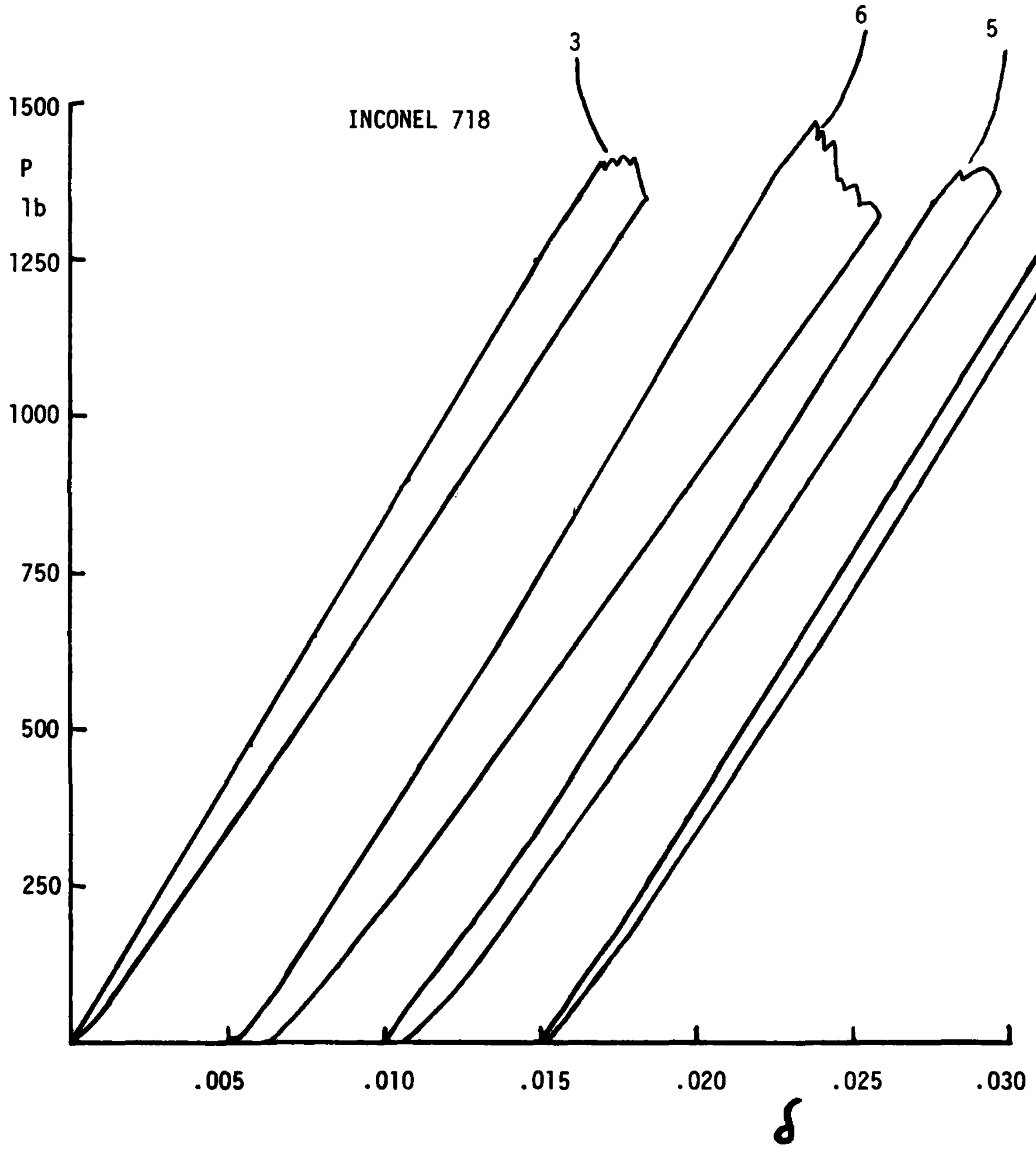

Figure 11. Load deflection curves for four Inconel specimens.

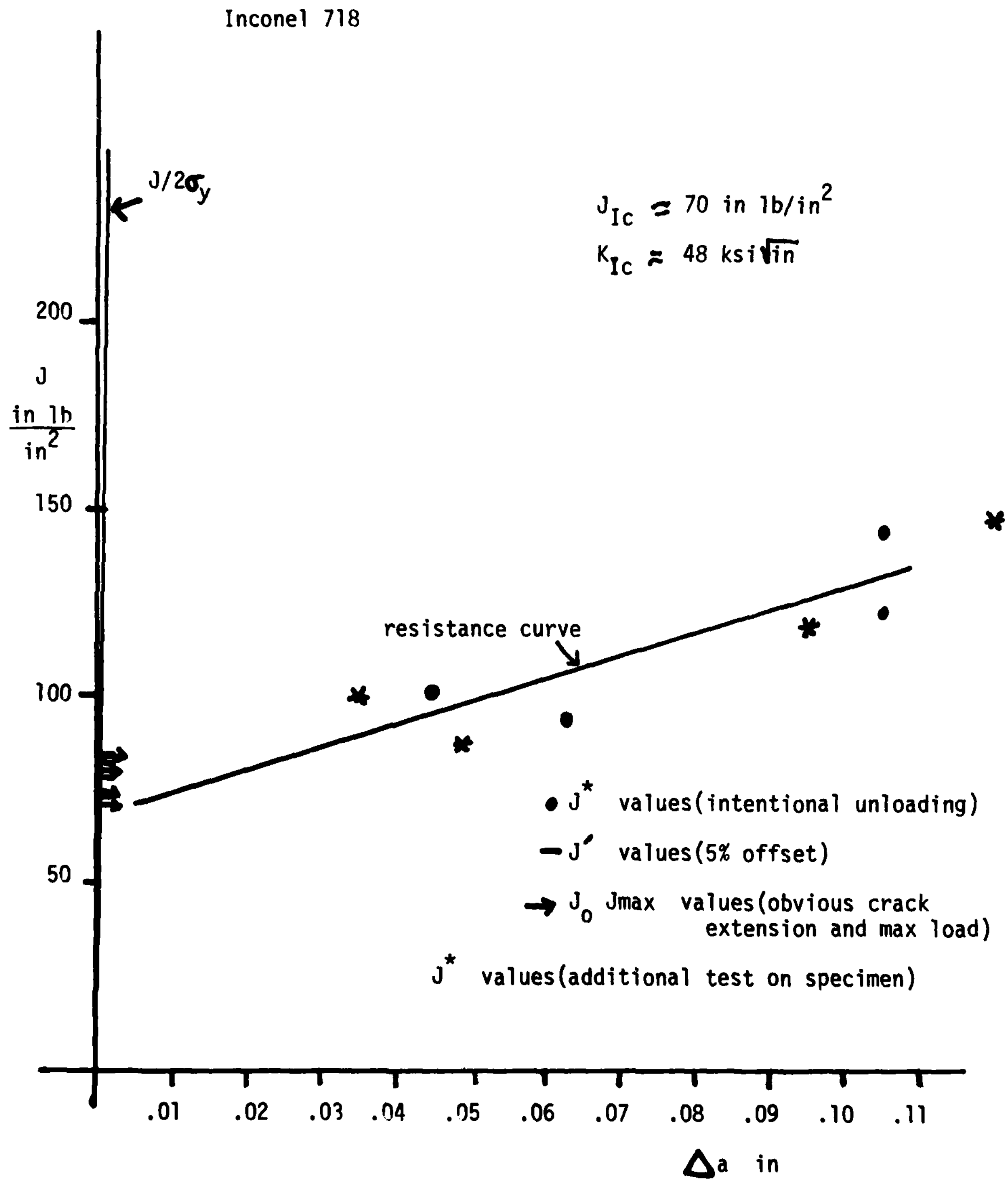

Figure 12. Graphical Determination of J_{Ic} for Inconel

TABLE 5

Test Results for Inconel (σ_y = 154 ksi, σ_u = 184 ksi) (A: in lb, J: in lb/in^2)

Specimen	No 3	No 4	/2	/3	/4	No 5	/2	/3	No 6	/2	No 7
B	.525	.525	"	"	"	.525	"	"	.525	"	.525
W	1.5	1.5	"	"	"	1.5	"	"	1.5	"	1.5
Δ_a	.063	-	.048	.095	.165	.045	.120	-	.105	.035	.105
b_o	.606	.590	.590	.540	.445	.587	.540	.361	.607	.505	.370
b_f	.552	.590	.542	.445	.279	.539	.418	.361	.504	.462	.275
A max (max load) and A (obvious crack extension)	11.9	-	12.0	10.7	12.3	12.4	10.7	5.5	13.6	10.6	6.9
A' (5% offset)	11.83	-	11.98	12.81	13.28	12.85	11.95	-	13.64	11.05	7.63
A* (intentional unloading)	13.78	6.6	12.63	17.0	18.48	14.35	16.31	6.24	16.39	12.16	10.58
J_o (J max)	74.8	-	77.5	75.5	105.3	80.5	75.5	-	85.4	80.0	71.0
J'_o	74.3	-	77.3	90.4$^+$	113.6$^+$	83.4	84.3	-	85.6	83.4	78.5
J^*_o	-	42.6	-	-	-	-	-	65.8	-	-	-
J^*_f	95.1	-	88.7	145.5	252.3	101.4	148.7	-	123.9	100.3	146.5

+ Too much specimen shape change.

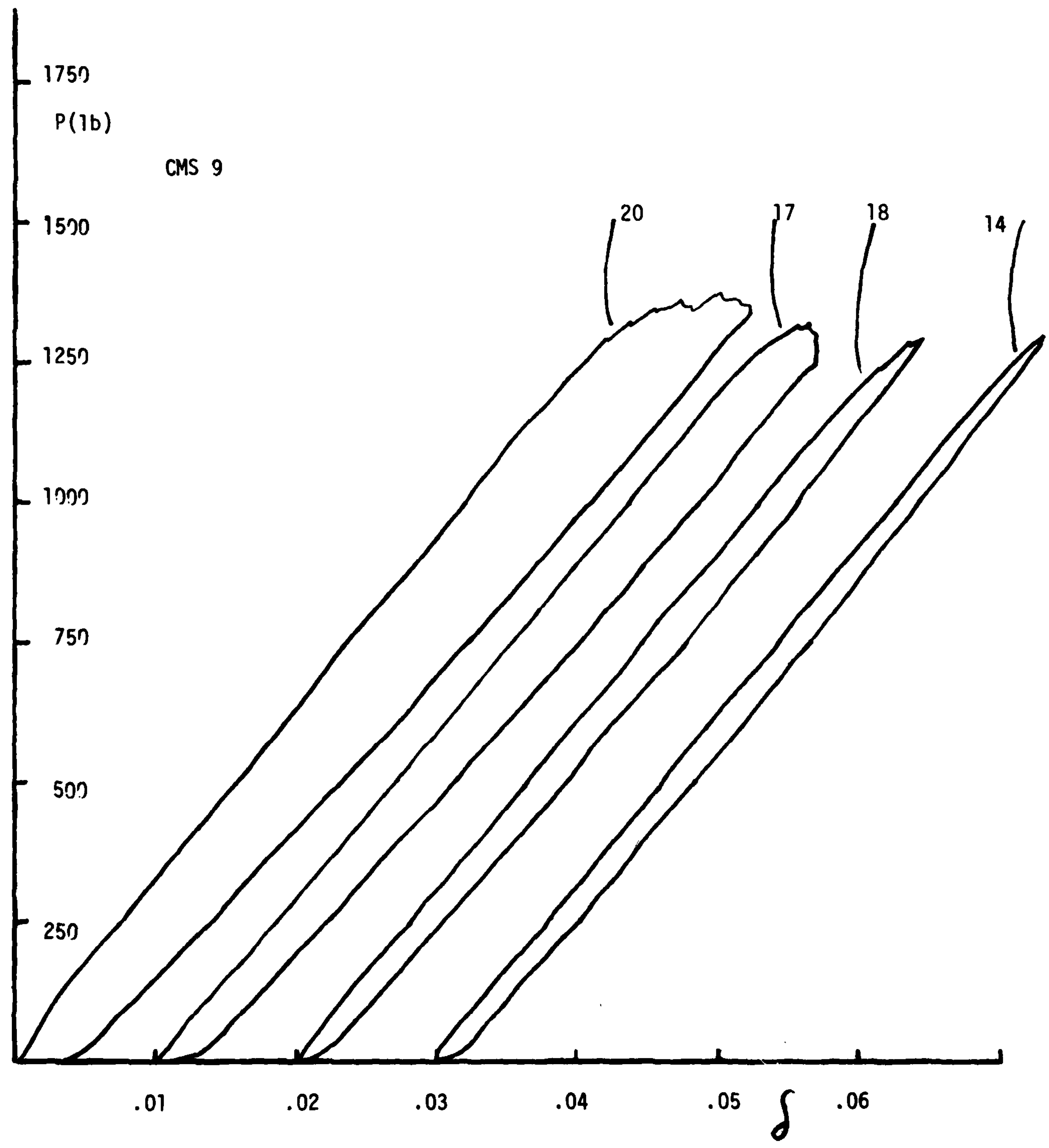

Figure 13a. P-δ curves for 4 CMS 9 specimens.

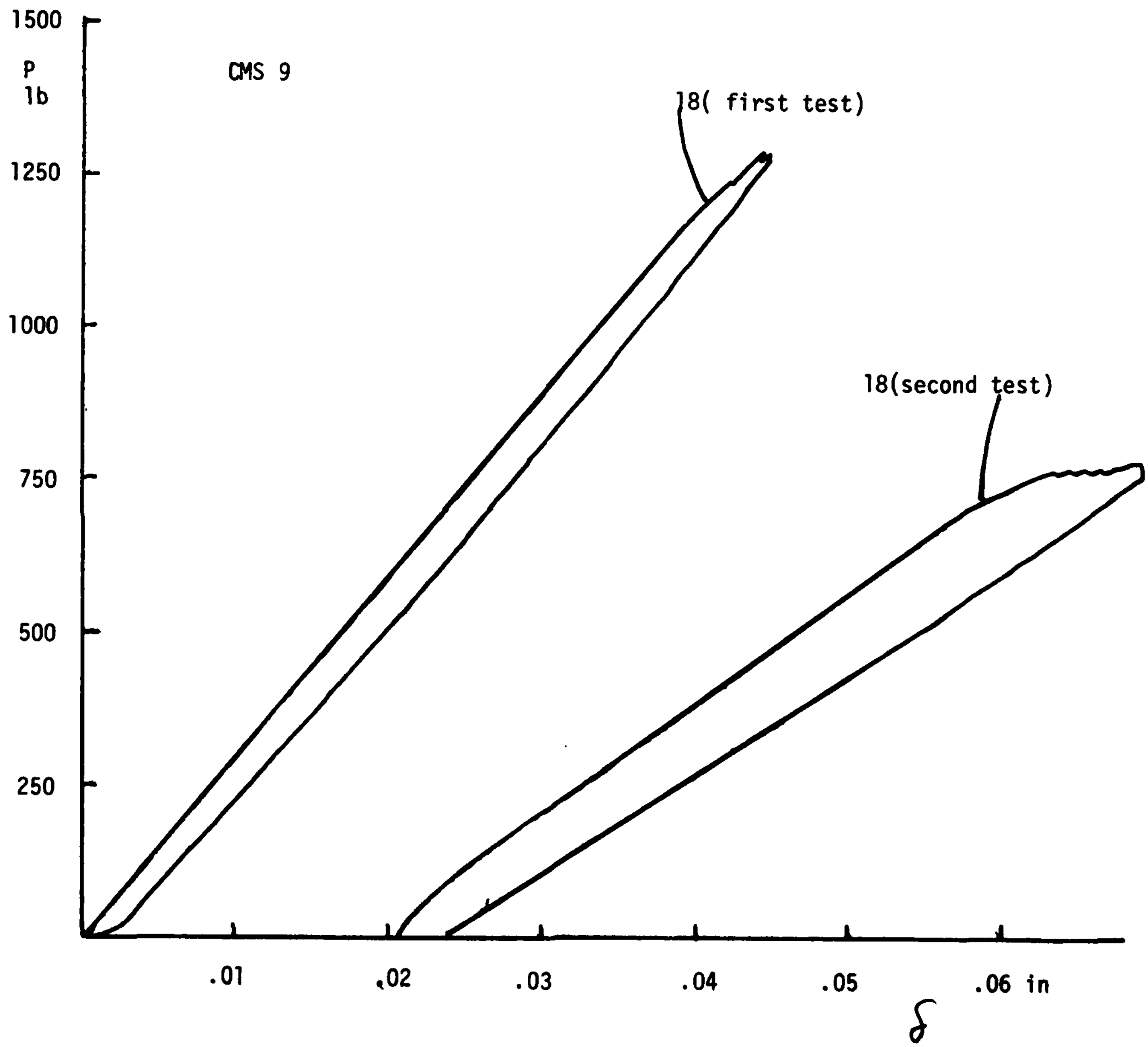

Figure 13b. P-δ curves for first and second tests on a CMS-9 specimen.

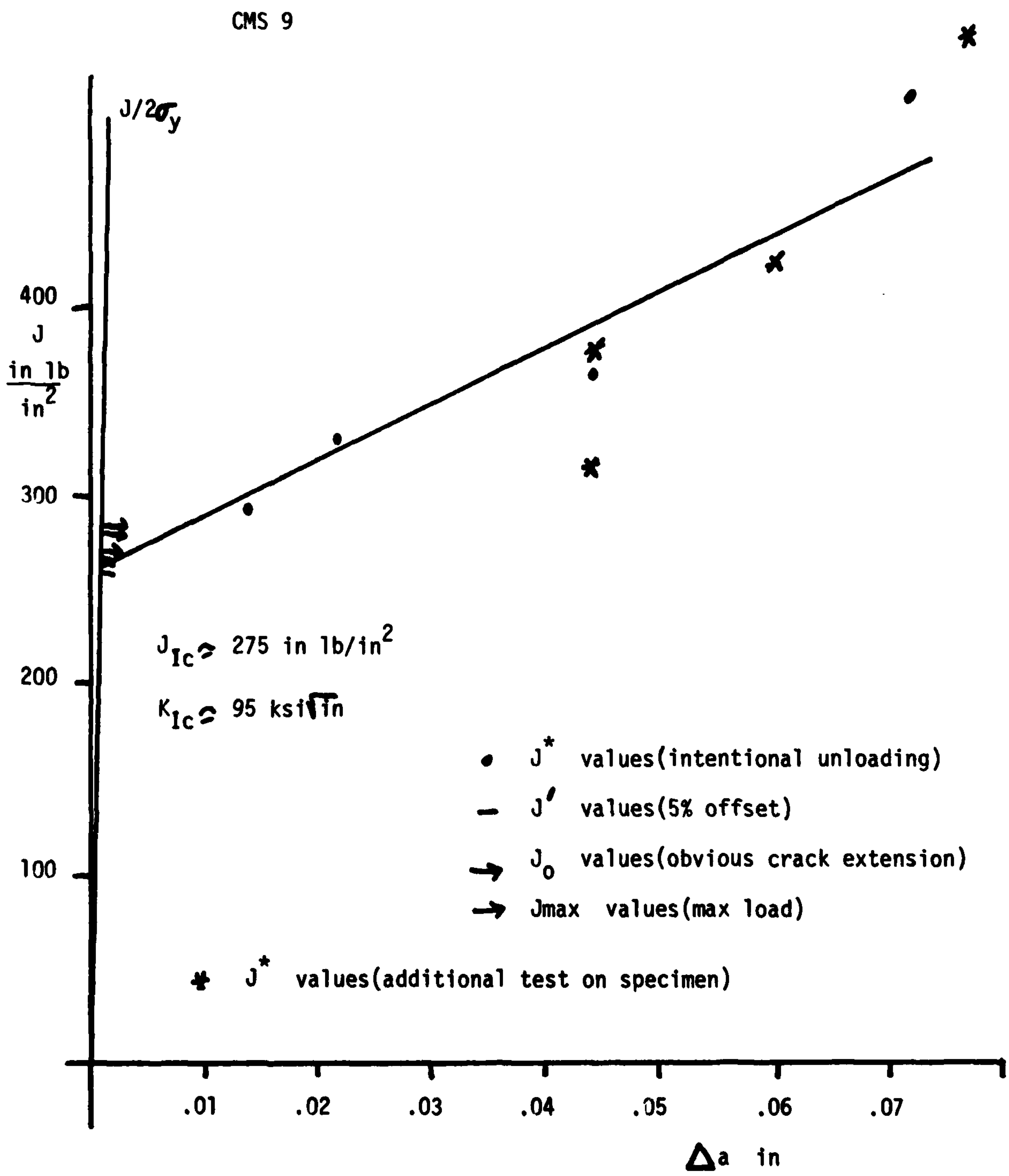

Figure 14. Graphical Determination of J_{Ic} for CMS-9.

TABLE 6

Test Results for CMS-9 (σ_y = 162 ksi, σ_u = 178 ksi)(A: in lb, J: in lb/in^2)

Specimen	CMS 14	2nd test	CMS 17	2nd test	CMS 18	2nd test	CMS 20	2nd test
B	.505	"	.505	"	.505	"	.505	"
W	1.00	"	1.00	"	1.00	"	1.00	"
Δ_a	.0138	.077	.044	.0605	.022	.044	.0715	.044
b_o	.396	.286	.400	.281	.383	.284	.395	.293
b_f	.382	.209	.356	.221	.361	.240	.323	.249
A max (max load) and A (obvious crack extension)	28.5	16.5	27.4	15.1	25.73	14.1	28.0	12.0
A' (5% offset)	26.88	11.33	27.05	11.29	25.13	10.68	24.35	11.19
A* (intentional unloading)	28.48	28.6	32.73	23.85	30.15	22.88	42.08	19.83
J_o (Jmax)	285	228$^+$	271	213$^+$	266	197$^+$	281	162$^+$
J_o'	269	542	268	427	260	377	244	315
J_f^*	295	157$^+$	364	159$^+$	331	149$^+$	516	151$^+$

+ Too much shape change.

(i) at the point where Δa is equivalent to $J_I/2\sigma y$

(ii) at the first drop in loading, J max;

(iii) at the point of 1st measurable crack extension;

(iv) at the specimen failure point "J_c";

(v) at the point where Δa is equivalent to $J/2\sigma_{flow}$ [14] where

$$\sigma flow = \frac{\sigma_y + \sigma_u}{2} \quad ; \qquad (7)$$

(vi) at a load defined by 5% offset in P vs COD [12] (corresponding to 2% crack extension);

(vii) through calibration, at the point in P vs COD indicating a 1 mm apparent increase in crack length;

(viii) by reducing the load by 10% and noting point where elastic unloading deviates from initial loading, (after Clark et al 1976) [11];

(ix) at the point of maximum load, J max; and

(x) at intercept of crack tip blunting line as defined by finite element methods.

No one method has seemed to satisfy each material under test. Brittle materials are relatively easy to deal with as they have flat R curves and the measurement point used affects the answer very little, Figure 15. On the other hand, ductile materials have steep R curves and the choice of measurement point can result in errors of up to 50%.

Since J_{Ic} is taken as the point of 1st real crack growth while K_{Ic} is taken at the point of 2% crack extension the results for J for a ductile material will be low (giving a conservative estimate of K_{Ic}). If one uses the 5% offset in P vs COD to define roughly the equivalent measurement point in the elastic K_{Ic} test then one obtains a closer estimation of K_{Ic} from the J_{Ic} test but the answer may not be considered conservative. It depends on what is required, an estimate of K_{Ic} through the J_{Ic} test or a valid fracture criterion for an elastic-plastic application. In this work it is felt, for these ductile materials, that both are of interest and accordingly both are evaluated.

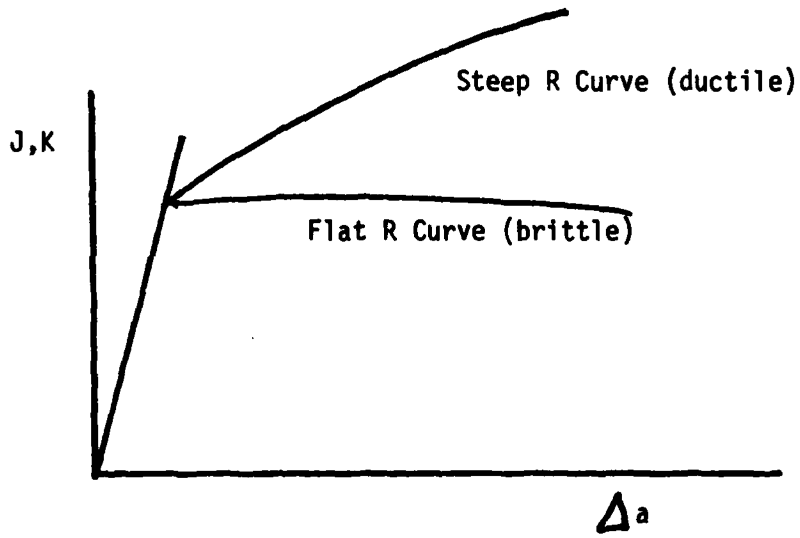

Figure 15. Schematic representation of the measurement point for ductile vs brittle materials.

J_{Ic} determined for each of the materials and an estimate of K_{Ic} are listed in Table 7.

TABLE 7

Material	J_{Ic}	J^1 (5%)	K_{Ic}	SLOPE OF R CURVE ($in.lb/in^2/in$)
INCONEL	70	78	48*	600
HY130	670	-	148	25,000
CMS-9	275	275	95	3,000

For HY130 the measurement point was taken at the point of lowest obvious crack extension and highest maximum load value determination for J. This material is very ductile and accordingly the 5% offset was meaningless and the intercept of the crack blunting line and R curve would have required many tests before any degree of confidence in the intercept could be reached.

*In laboratory tests for K_{Ic}, the DREP Corrosion Group also measured a value of 48 $ksi\sqrt{in}$, following ASTM E399.

This high ductility material is characterized by the steepness of its R curve at 25,000 in $lb/in^2/in$.

It was found for Inconel 718, a relatively brittle material (as ductile materials go), with a slope of its R curve at 600 in $lb/in^2/in$, that all methods for J_{Ic} determination were valid. For this degree of ductility, the second test on the same specimen gave consistent values on the R curve but not with the 5% offset method after the second additional test. It appears then that one specimen could not be fully relied upon to give a complete estimate of J_{Ic} by the 5% offset method even for this relatively low ductility material.

The actual toughness value for the Inconel was low because of the intergranular nature of the fracture and the correspondingly low energy needed for crack propagation. It should be noted, however, that the grain boundary precipitates that promote this type of fracture are necessary to stabilize the microstructure at high operating temperatures.

For CMS-9 each of the measurement point techniques gave close approximations to the same J_{Ic} value. The lowest of the J max values or the highest of the 5% offset values seemed to coincide well with the intercept of the R curve and crack tip blunting line. For this medium ductility material, (R curve slope = 3,000 in $lb/in^2/in$) second tests on the same specimen are basically invalid.

In terms of a reliable single specimen test it would therefore remain to develop the computerized systems for detailed evaluation of the Clark[11] method. However, the relative ease of the multiple specimen test would make this a marginal pursuit.

CONCLUSIONS

1. J_{Ic} measurement points were determined by plotting the J integral test results in the form of a resistance curve and comparing various selection points for J evaluation in the vicinity of the crack blunting line.

2. The validity of J_{Ic} as determined by using the 5% offset to the load vs crack opening displacement curve as the measured point is dependent upon the degree of ductility of the material. When the R curve is steep (greater than 5,000 in lb/in^2/in) indicating high ductility, this technique appears to become invalid. In the case of the HY130 steel a 5% offset in P vs COD occurs before any crack growth.

3. The elastic-plastic fracture toughness J_{Ic} and plane strain fracture toughness K_{Ic} as determined for the HY130, CMS-9 and Inconel are respectively 670 in.lb/in^2, 148 ksi $\sqrt{in}$; 275 in.lb/in^2, 95 ksi $\sqrt{in}$; 148 in.lb/in^2, 48 ksi $\sqrt{in}$.

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Determination of the elastic-plastic fracture toughness for threee medium strength materials of varying ductility has been carried out. The materials in decreasing ductility are HY130 Steel, CMS-9 Steel, and Inconel 718. A survey of measurement-point techniques for J_{Ic} has been incorporated in the study to evaluate the effect of ductility on the determination of both an elastic-plastic fracture parameter and a fracture toughness measure for direct estimation of the elastic fracture toughness K_{Ic}.

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